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Sincerely,

Martin A. Gundersen
Principal Investigator

PLASMA-ENHANCED COMBUSTION FOR REDUCTION OF ROCKET PLUME SOOT

FINAL PROGRESS REPORT

MARTIN A. GUNDERSEN P.I.

DECEMBER 2001

OFFICE OF NAVAL RESEARCH

GRANT NO: N00014-00-1-0098

Grant Title/Number: "Plasma-Enhanced Combustion for Reduction of Rocket Plume Soot"
Grant # N00014-94-1-0098
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Major Accomplishments:

We have demonstrated the application of transient plasmas for remediation of emissions both during and post-combustion. The project encompasses underlying physics and chemistry, plasma device and power conditioning engineering, and problems related to fabrication of practical devices. The major accomplishments include demonstration of an energy efficient approach, which is now being used for many plasma remediation applications, development of the knowledge of the underlying science including the role of transient plasmas, development of diagnostic methods including laser induced fluorescence, and identification and new data on a solid state approach to pulse generation.

The application of laser induced flourescenceis to the measurement of NO and NO_2 densities in atmospheric pressure flows, the 'bad characters' in diesel emission, to develop data for incorporation into microscopic models of the plasma processes. The data is still being developed and interpreted, but indicates that the most effective results (NO conversion) occur associated with the formation of streamers, localized near the streamer site. A paper describing this work is listed below.

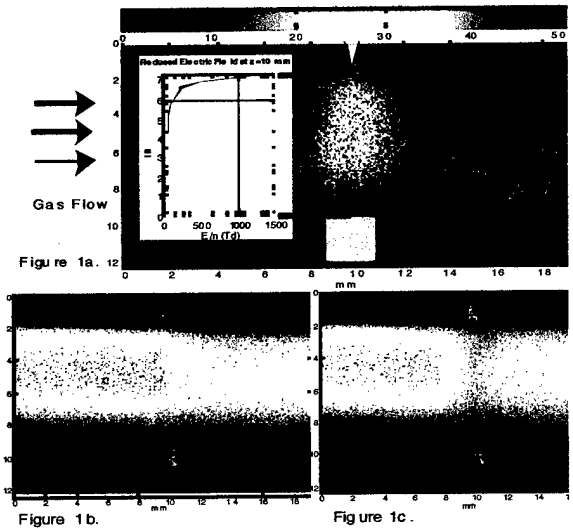
We are also developing modulators to match the discharge/reactor impedance, a complicated function, because the plasma is varying in time, and the impedance is also changing. This power conditioning requires that a specific design be fabricated to match specific pulse conditions. Factors include the limitations of present day switches, and certain other components. Further, we are working on the development of necessary pulse generators. The pulse generators for the regime required are normally thyratron-based, a constraint that arises because the combination of voltage (typ. 30kV), current (≈50-1000A), and pulse rise time (≈25nsec) has not been achieved with solid state. We are seeking to develop a solid state version of the pulsed power generator required for this work. Such a generator was completed as a prototype using an "adder" approach. The pulse generator is also being successfully used for an application to microwave generation under study by a collaborative group at USC and UCLA (another program under Prof. T. Katsouleas). We are now working on the next version, to improve the rise times, power handling capability, and address fabrication issues. We have also tested several reactors, and a range of the parameter space that affects this approach. We found best results with a corona reactor, tested with a diesel engine connected to a generator (used as a load). Details are provided in two technical publications (Appl. Phys. Lett. 71 (23), 3364 (1997) and Proceedings of the 1998 SAE International Fall Fuels and Lubricants Meeting, San Francisco, CA, October 19-22, 1998).

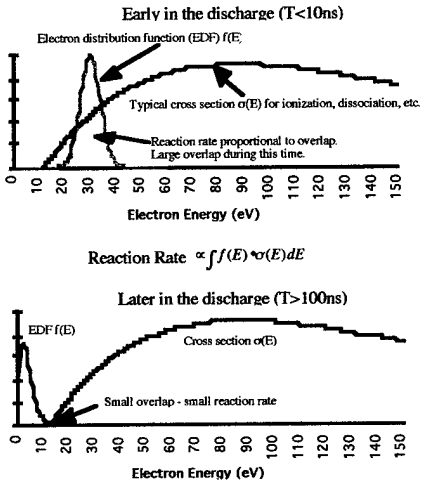
The project has formed the basis for further work carried on since the ONR period of performance, and was essential in initiating this. New research for which the project provided a foundation includes development of approaches for reducing delay to ignition for various fuels

including methane and ethane, using a transient plasma for ignition. The results to-date include observation of a reduction in ignition time by *typically a factor of 3, for the various fuels, and for varying equivalence ratios at atmospheric pressure*. This work is currently underway, and will reported in the near future.

ONR Contracts/Grants:

U.S. Office of Naval Research Grant # N00014-00-1-0098 - "Plasma-Enhanced Combustion for Reduction of Rocket Plume Soot"





Caption: Left: Shown above are LIF images of NO before (figure 1b) and 10 ms after (figure 1c) a pulsed negative corona discharge in 25 ppm NO seeded air. Figure 1a is the difference between the two images. The gray regions indicate the electrode location. Gas flows in from the left-hand side, while the laser propagates from the right-hand side. The inset on figure 1a is a plot of the calculated reduced DC electric field as a function of position in the gap for the centerline of the electrodes. Right: Graph illustrating the effect of 'short pulses'. The upper graph shows that electrons (green line) with energies above a few eV will be much more efficient in overlapping with relevant cross sections. The lower figure shows the electron distribution associated with an equilibrated plasma, and the non-overlapping character (the average energy is too low). The point of the graph is that during the initial transient phase there will be electrons with higher energies, and hence much more efficient for ionization and dissociation.

The solid state pulse generator work described in above is important for the DOD. This work is attempting to replace thyratron-based pulse generators with solid state-based systems — leading to smaller volumes and lighter weight. The work is important for applications including radar, lasers, microwaves, and commercial as well as DOD pollution abatement, where miniaturization, low cost, and robust operation is both desirable and enabling. These accomplishments make possible a cost effective, energy efficient approach, previously thought unattainable.

We have worked with a major diesel company to arrange initial testing. We have been in contact with, and have been contacted by, major electronics, automobile and catalyst companies. Some of them are Hughes, Raytheon, Engelhard, Ford Motor Company, Detroit Diesel Corporation, Siemens. A large number of other contacts have occurred with industry. At

present, industry is scrutinizing this approach closely — with activity in Europe, Asia, South America and North America.

This research has also been cited in the following scientific publications and popular media:

"Death Rays to Zap Diesel Pollution?" -- *Business Week*, July 1, 1996.
"Pulsed Power Cleans Diesel Exhaust" -- *Inside R&D*, July 1996.
"'Star Wars' vs Smog" — *Los Angeles Times*, June 19, 1997.
"High-Tech Help for Dirty Diesels" -- *MIT Technology Review*, May/June 1997.
"Short Pulses Show Promise for Treating Pollution" -- *The Ballistic Missile Defense Organization Update*, Spg 97.
"BMDO R&D May Help Meet Clean Air Standards" -- *1998 BMDO Technologies—Improving the Environment.*

Research articles published: (Total number generated, parts or completely from ONR funding): 25

3 most significant archive publications, book/book chapters, patents:

"Energy efficient plasma processing of gaseous emission using short pulses, " V. Puchkarev and M. Gundersen, Appl. Phys. Lett. 71 (23), 3364 (1997).
"Plasma processing of diesel exhaust by pulsed corona discharge," V. Puchkarev, G. Roth, and M. Gundersen, Proceed. 1998 SAE International Fall Fuels and Lubricants Meeting, San Francisco, CA, October 19-22, 1998.
"Laser-induced fluorescence images of NO distribution after needle-plane pulsed negative corona discharge," G. Roth and M. Gundersen, IEEE Trans. Plasma Sci. **27**, pp28-29, (1999).

Patents: "Repetitive Power Pulse Generator With Fast Rising Pulse" (File Date: 5/3/00, USC-2956, 06666/062001)